

PROPULSION SYSTEM NEEDS  
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I would like to pick up where I left off in the presentations yesterday relative to the needs of the designer of a solid core nuclear rocket engine; things that he needs to do or needs to understand in order to focus his design effort and his analysis.

Now, I will put the "strawman" propulsion requirements and engine cycle up to illustrate a couple of points. Chamber pressure is first.

This particular design (see Figure 1) was very arbitrarily selected at about 1,000 psi and I will go through the factors that led us through that selection. There is a lot of flexibility going up or down in the chamber pressure.

The impact of this parameter is mainly going to be in the size of the engine (particularly the size of the nozzle assembly). It is important that we understand what the trades are in terms of the size and the configuration of the overall envelope of this engine.

Assuming that we wanted to go for an expander cycle (see Figure 2) in order to maximize our chance to get reasonably high Isps, we did not want to have some of the total propellant flow not contributing fully to the thrust and the Isp we can realize. If all of the weight flow is heated to the maximum temperature and is expanded to the full nozzle expansion ratio (epsilon), you will always do better.

The point is that the designer has several sources of energy to be able to heat the working fluid that's going through the turbine. It doesn't have to be all of these sources -- just those that heat the working fluid to the desired turbine inlet temperature before joining the main flow when it goes down through the core on the final pass. The source of energy might come from the cooling of the nozzle.

Now, that's a poor place to get the heat if you can avoid it because it is coming out of the gas that is expanding through the nozzle of the main thrust. It represents a small, but still finite impulse loss. It is better to take it out above this station because any energy you take out in the form of expansion across the turbine stages can be added back in by the core. You can get that for free, except for the weight of the structures involved.

One attractive place to get it is from a coolant loop in the core. This loop is used solely for the purpose of heating that portion of the total flow that is used to drive the turbine. In the kind of reactors that we looked at in the past, the tie tubes were also an attractive way to get that energy.

In this particular system diagram (see Figure 2), we shown a split. I will assume, for the

total flow coming out of each pump, 50 percent goes down through the tie tubes and 50 percent goes down to cool the nozzle, and up through the reflector. Of that portion that goes through the turbine, a portion bypasses the turbine for control. The flow needed to actually develop the shaft horsepower goes down through the turbine and then down into the core, joining the flow from the reflector. All of this becomes one approach.

It is only necessary that we provide the measures needed in order to get adequate turbine pressure ratio and adequate pressure drop across the passages. They don't have to be balanced. They will get balanced when they come together. At that point there may be some imbalance, but it doesn't really hurt you any.

Now, we really have two very powerful knobs, in addition to weight flow, to get the necessary shaft horsepower.

In Figure 3 we have plotted chamber pressure as a function for various pressure ratios across the turbine (e.g., 1.1, 1.25, 1.52) and for various temperatures coming into the turbine. From this you can pick off the case where there is turbine bypass and which represents the maximum power that you can get.

Now, in this particular case you can see the trend. Fairly cool gas with a fairly high pressure ratio can get you to reasonably good chamber pressures. If you go on up in temperature of the gas, you can get higher chamber pressure and if you go on up to higher pressure ratios, you can get higher yet. If you go up to 1,000 R, your way is open to go to very high chamber pressures.

The question really is where do we want to be in pressure chamber? Only a portion of flow is going through the turbine because we don't need it all: e.g., less than 50 percent of the case we want through here. We can get the shaft power.

If the control valve is shut, the result is the condition of maximum power that I can develop from the portion that I have diverted into the turbine loop. Remember now that I took the other half of the total core flow and said I am going to use it to cool the nozzle and the reflector.

So we have a capability of going on up in chamber pressure and coming way down in the size of the nozzle, if that's what we should do from the engine size point of view.

Now, there are some that feel high chamber pressure equates to high risk. Well, I would like to say that I believe that's a myth. It's doesn't having anything to do with chamber pressure; it has to do solely with design margin.

A VOICE: Off the top of your head, would you accept as you went up in chamber pressure that flow -- required to power that cycle would have to and become a point where you can't go any higher.

Don't you run into a point where your area of the throat really becomes too small and you have a heat transfer problem on it?

MR. GUNN: What we did in our Phoebus designs is to go into tube splices or joining together of coolant passage design so you can cool down to very narrow slots in the design of the throat area. But you are right, there is a limit.

But I am trying to make the point that at 1,000 psia or 1,500 or even 2,000, there is no reason that you can't pick up and get an adequate design with an adequate throat area. For the hundred thousand pounds of thrust we have talked about, we have an eight inch float area.

A VOICE: You are really limited in chamber pressure by what you are comfortable with and the maximum heat flux of the throat?

MR. GUNN: True. But, I am not advocating up to 3,000 or 4,000 thousand psia. I am saying it is within the range of 1,000 to 2,000. I am comfortable that we can come up with a design that will work. But the real question is do we want it that high for reasons of size?

Now, there is another benefit that comes out if you go up in chamber pressure and that is the density of the working fluid that is going down through your core is increased and therefore the pressure drop across the core is reduced. But you are removing more heat per channel and the thermal stresses in that fuel element are going up. At some point, it is going to be the power density that limits the increase in chamber pressure/thrust level.

I should say that this is based upon a solid type of core where you have the thermal stresses associated with where the heat is generated how it gets to the surface. You are right.

This chart (Figure 4) starts off with the old famous Phoebus 1B test that we ran. What we did to come up with these parameters was simply take the test data that we had from that run, relative to the reactor, and put an engine cycle around it that was an expander cycle.

Now, note on this particular setup we have started off with a reactor exit pressure that was about 750 (735) psia. We ran that test and we said if we had simply sped up the pump, gotten more pump discharge pressure, we would have gotten to a higher chamber pressure and higher power level.

We had put design margin in the Phoebus 1B test hardware to go to 1,000 psi. We would have gotten the 2,000 megawatts. One route to get more thrust out of your engine and your given reactor is to simply speed up the pump and get you to the higher discharge pressure. Then you will automatically get the higher power density, up to the

limit of what the core can deliver.

There is another way that you can upgrade: composite fuel (see Figure 5). Instead of going on up in chamber pressure, you might choose to open up the throat area.

That will get you to a higher thrust about the same pressure at the pump outlet. The pressure drops across the nozzles coolant passages and the reflector, but it does result in an increased delta P across the core. For an assumed flow rate of 108 pounds/second, we had the difference between chamber pressure in this case of 1,333 over a 1,000, as compared to the reactor inlet pressure of 1,506 over 1,231. The difference here you can see is 231 psi, the difference here is about 170. So there is that effect.

And if you try to get your higher thrust and for the same core get a higher thrust to weight ratio by opening up the throat area, you are going to increase the pressure drop across the fuel elements.

Now, let's talk a little bit about nozzles (Figure 6). In this particular case we are looking at a 75 K engine and we are using composite fuel element, 4,860 degrees R in the thrust chamber and the Isp of 918 seconds, and 1,000 pound chamber pressure.

Well, as I indicated to you yesterday, if I maximize Isp, and I want to get the maximum in terms of expansion process, I get a very long nozzle. In this case 14 feet by 26 feet. This configuration creates concerns about where you store this thing and so one possible way to do that is to embrace extendable nozzles. The other way is to invert the nozzle skirt, but then you have the problem of getting the astronauts out there to bolt everything together.

But as you see, this package is fairly long. You might want to make a double truncation of the nozzle as a way of making the packages smaller. You could also consider going to expansion deflection nozzles or a torroidal nozzle. You can really pull down this size with such a technique, but that's adding the complication of looking at a more advanced configuration.

Another factor is that a portion of the diverging section of the nozzle now is going to see neutrons coming out of the core. They are going to be scattered and there is going to be some contribution of this projected source area of neutrons that have to be contended with relative to interaction with the hydrogen in the tank, and producing secondary gammas. If you are trying to cover yourself on that one, you might have to extend the shield to a larger diameter to be able to effect that.

A VOICE: Do you have a feel for what kind of neutron flux would be there without the shield?

MR. GUNN: I don't have that today, no.

However, one of the Russian scientists I talked to in May suggested a way around this problem, which was to go to multiple nozzles: nest together a group of short nozzles rather than one big one.

Then again you get into not only the throat heat load problem, but you also get yourself into a situation where you have more drag and more boundary layer to contend with and that's going to be an Isp loss. So these are factors to worry about in the design of the nozzle and this again points out the need to understand the payoff, as far as the vehicle contractor is concerned, on the package size.

A VOICE: The nozzle would seem to be significantly shorter, if you went to multiple nozzles.

MR. GUNN: That's right, and for some applications, that would be a neat way to do it.

A VOICE: If the nozzle is going to weigh more, you aren't going to get the full benefit.

MR. GUNN: That's part of it. I tried to see how much net benefit comes out. You have to go through that and find out how far do you want to push that. If you have carbon carbon or carbon composite, a light weight structure, you might elect to go farther than you would on rhenium or something like that. You would also be limited by manufacturing facilities.

Now yesterday I talked a little bit about dual turbo pumps and you asked the question. I said, yes, it was done and you were with us out in Nevada.

A VOICE: I know NERVA did. I said any real rocket.

MR. GUNN: We thought that was a real rocket.

A VOICE: It never flew.

MR. GUNN: It didn't fly.

A VOICE: You are telling me there was never, that there has never been a chemical rocket with multiple turbo pumps?

MR. GUNN: I am not sure, because the Russians have been pushing for multiple turbo pumps in some of their approaches and I am not sure where they stand.

A VOICE: My understanding really comes back to the business of multiple engines that I would argue strongly that multiple engines are better than multiple components on one engine, but that's another issue. That's really what I was asking.

MR. GUNN: I thought, had you ever done this, and the answer is, as far as pumps running together and working harmoniously, and designing a system that you could have a pump failure and you keep right on going, that was done.

Now, I have shown two. Is that the limit? No, it is not. We are looking at three, and if you put three in these things you can put a nice balanced thrust structure and fuel delivery lines and you can run a full thrust if you had a failure of one of the units. It's like on an airplane with multiple jet engines on a transport that we go across the country in. How many do we want to put on: two, three, four, eight? In some cases it is two.

A VOICE: They don't have multiple fuel pumps.

MR. GUNN: No, but I am trying to make a point; multiplicity. I think you are raising a good point, but I think one could argue that if you examine all of the components in the engine and ask yourself what gives you the most grief or gives us the most concern, I am going to say and surprise the people by saying I don't think it is the reactor. I think the reactor can be designed very robust, and forgiving to a certain extent, because we saw that in Nevada. We saw malfunctions occur. There can be some degradation, some erosion, some cracking of the fuel if it is a solid and still it will meet its job. But the turbo pump failing is catastrophic.

A VOICE: In the aircraft industry with engine out capability, those engines are designed for 30,000 hours of operation. We are talking about a maximum of ten hours. Now, with that sort of a situation, there can be a lot built into the design because you are really down very, very low on what I would call the life requirement.

MR. GUNN: Against what components are you looking at for failure?

A VOICE: I am looking at only the turbo pumps, the turbo compressor?

MR. GUNN: If you look at a blade on a turbine and look at the vibrations it can undergo on your Goodman Diagram curves, you find within minutes you can get yourself way out on the curve because you have such high vibration rates.

A VOICE: That has to be worked out in the design but in the aircraft industry we are talking about 30,000 hours of operation on those engines.

A VOICE: In the rocket industry, when we have had failures, the bottom line has been the support systems which can cause the catastrophic failure and not the engine. The RL-10 is probably the best engine ever built.

A VOICE: What I am trying to get away from if at all possible would be the concept of dual turbo pumps because of the short time of operation. I recognize the vibration problem.

A VOICE: Part of the problem in solid and liquid rocket engine development and with the shuttle is that they are technologies; the engine is too full. By doing a full systems test, we would have probably done a lot better. In other words, try before you fly.

With the dual turbo jump concept, I really question what we are gaining because we do have the added components and the complexity.

MR. GUNN: You are into the question of redundancy versus complexity. It turns out that the weight of the turbo pumps is a very small fraction of the total thing. You go to dual pumps, each one a little smaller, so it becomes lighter, but the two are heavier.

MR. HANNUM: We keep running down to Johnson to ask what does it mean to be man-rated: we keep asking them and the answer always comes back rather vague. But there are two points that they make consistently. One is that astronauts like redundant systems. You could argue that redundancy by virtue of it being there reduces liability. And it sometimes does. Redundancy sometimes does reduce liability.

Now, all the things that you all are saying about redundant turbo pumps and the pain and agony that goes with them is all very true. What we need to do is make the trades that Stan is arguing about and be prepared then to ask what does it do to reliability to have these? Redundancy is considered as "goodness" until you can prove it otherwise.

MR. GUNN: It's possible for us to design an engine system that requires no shielding to protect itself against its own created environment. The driver on that is to get the weight on the engine down and get the thrust to weight up because some of the shield's weight are not trivial.

Now, it still may be that you need to have the shield located in the engine area and maybe it's within the dome. Maybe it is above the dome. It depends on what temperatures they can stand relative to shielding against the neutrons and interacting with secondary gammas. In any case, I contend that it is possible to engineer every piece of equipment in this engine so it can take the full flux of reactor radiation and keep right on going.

I am going to point toward a system that doesn't use electronics. If it is necessary for redundant controls to go a separate system that is electrical and have them still work in a way that they could operate successfully, then you either have to shield the sensitive electrical parts or move them somewhere else to get them out of the radiation field.

Let me just address this first issue, which is pumping hydrogen. It is traditional that you have to have positive NPSH, and in dealing with liquid oxygen and some of the other propellants, that's true. Hydrogen is unique; you can pump it in a boiling phase even ingest up to 30 percent of the volume being received as vapor, and still pump alright (Figure 7).

When you trade that capability through the tank pressure, etc., you can convince yourself it is possible to pump saturated fluid in a tank at full thrust conditions, provided you get up above a certain minimum level in tank pressure.

I am not prepared to say that I am taking the tank pressure down to five psi, but I think anywhere from certainly 20 and above psi you can do that. And here again we need to have the people responsible for the tank design for the mission to tell us what working pressure they are going to go to. Then we can see if we can do this.

A VOICE: I was saying that one of the important things in this would be to work with the triple point hydrogen to get the better impulse density out of it and take all of the advantages.

MR. GUNN: I showed you earlier this control system (Figure 8) that's insensitive to the radiation environment. The fundamental parameters we need are pressure and temperature. We can get that. From that we can get the weight flow and the temperature. We know then what the reactor is doing, relative to its scheduled delivery gas temperature. Then we can operate on a schedule of thrust buildup, holding for thrust and thrust decay and meeting the mission requirements.

Shown also is a flux sensor. I think we need that I think for two reasons. One is that when we start the buildup, we start evolving from a very low power level until we start to see some significant power. You need to understand where you are and how fast that rate of power increase is occurring.

Then after the firing is over and you have shut off the propellant valve, the core now starts to heat up. You need to know when to introduce propellant flow again to pulse cool if that's the mode you are going after.

And one of the things that could give you that is the flux sensor. Perhaps the parameter I will show you next is the better way to do that. The question is what part of the core will tell you that other parts of the core are getting up close to the limit you want to see it operated at?

I make the contention that I am making a primary measurement of temperature and the neutron flux. I am going to use that measurement as a primary input, along with my pressure measurement, to determine everything else I need to do in that system.

Once you have made the shutoff and you have closed the propellant valve, you follow a curve on the decay power. That power is going to cause the core (after you have undercooled or overcooled it) to creep up again in temperature. Then you have to try to extract maximum Isp from the coolant gas, if that's what you want to do.

There is a neutron flux sensor that was conceived and worked on that back in the 1960s.



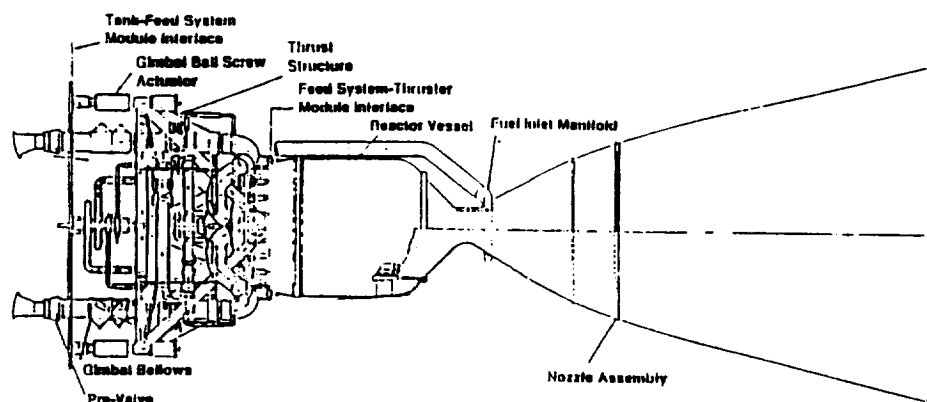
It is a temperature sensor that senses the output of the gas coming down out of the core directly and gives a pneumatic signal that's proportional to the temperature. We were also looking at pyrometers to get in and be able to measure surface temperature and maybe the core cylinder that needs to be monitored to say whether the internal core is getting too hot. We also did a lot of work on radiation resistant valves and actually deployed some of those in the NRX test series.

One last area that might deserve attention is an alternate way to get rid of this decay heat; that is a core cooling system. This was an old concept back in the 1960's. It was basically trying to tie into the heat removal capability of the tie tubes. With a closed cycle system, involving a turbo compressor and radiator, we could take the problem of having to use propellant to be able to remove the decay heat, and convert it into a means of radiating heat to outer space. We could thereby save the propellant for use in the later burns in the mission. It trades off that advantage with complexity because here is an added system of added weight. I am not sure that that's a smart thing to do, but it is a possibility.

Much of the improvements I have talked about here are a way of trying to get better specifications for the engine: that is Isp and engine thrust-to-weight ratio.

You have to be specific on what part you are talking about on this thing. Some of the things we know enough about so that if you retrieve the information, you can just go ahead and do it. A lot of other things are going to take development.

# 100K FLIGHT THRUST MODULE/FEED SYSTEM MODULE ASSEMBLY



Is ( $\epsilon = 500:1$ , UNCOOLED SKIRT) 922 SEC  
WEIGHT.....18,000 LB  
FLOW RATE.....108 LB/SEC

$\epsilon$  (COOLED SKIRT).....150:1  
POWER DENSITY.....85 MW/FT<sup>3</sup>  
ENGINE CYCLE.....EXPANDER

Figure 1

## 100K NTR, Expander Cycle, Dual T/P Tie Tube Turbine Power

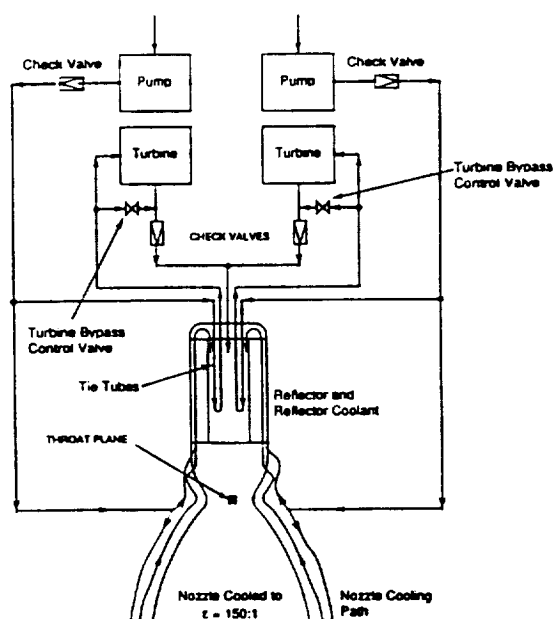


Figure 2

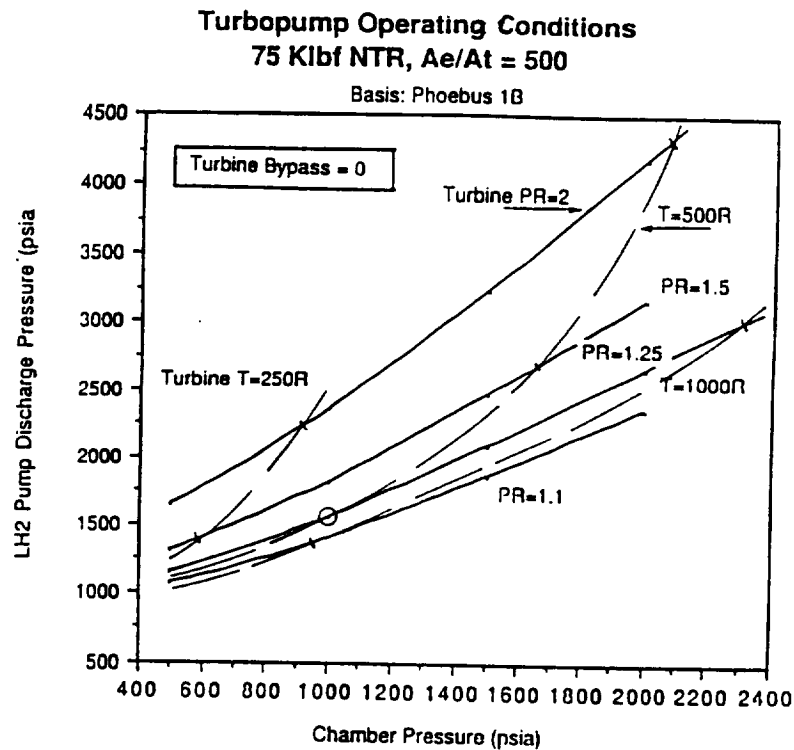


Figure 3

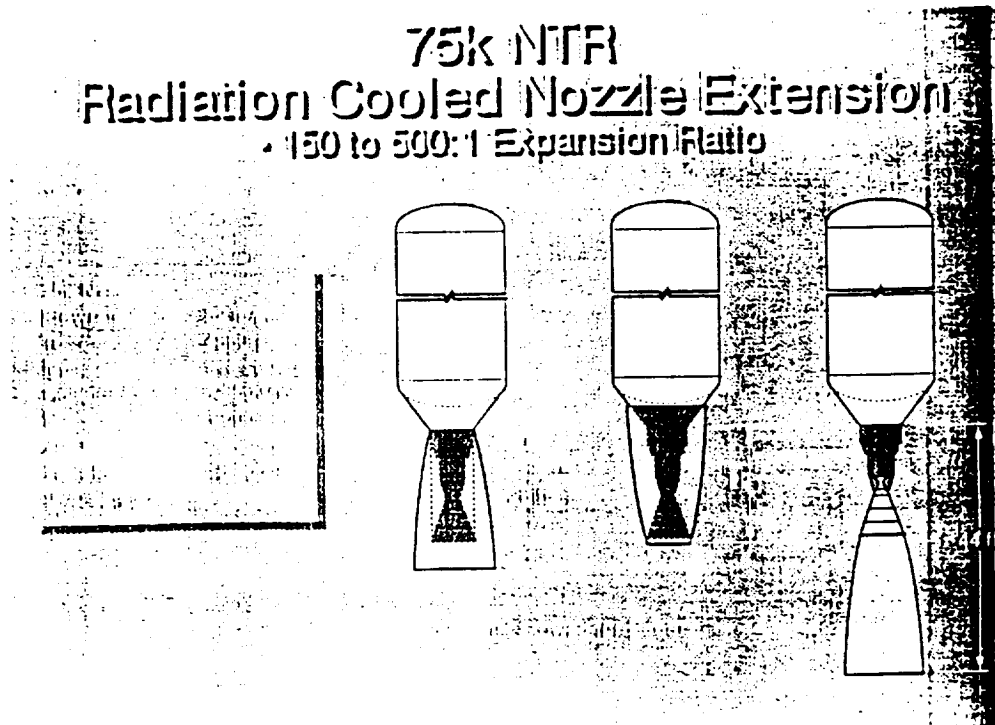
### Typical System Parameters

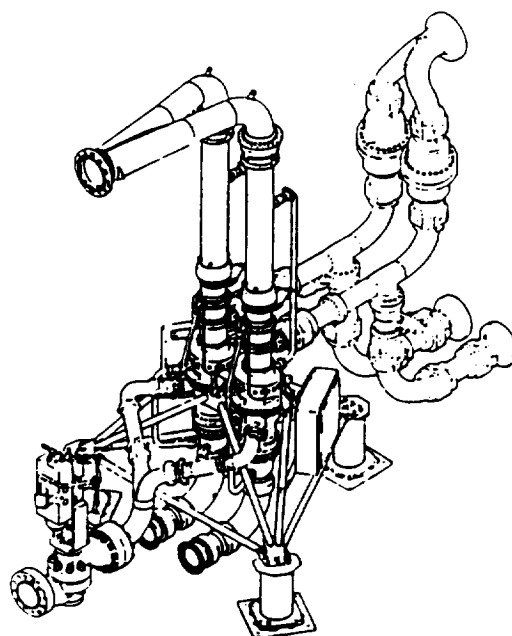
	<u>Phoebus 1B</u> <u>75K Thrust Test</u>	<u>75K NTR</u> <u>Composite Fuel Elements</u>
Pump flowrate, lb/sec	110	81
Pump disch press., psia	1381	1544
Turbine flowrate, % pump	11 (Cold Bleed)	50 (Expander)
Turbine Inlet temp, °R	600	1000
Turbine Inlet press., psia	531	1412
Turbine pressure ratio	10.4	1.25
Reactor Inlet pressure, psia	938	1130
Reactor power, MW	1455	1645
Reactor core flowrate, lb/sec	94.4	81
Nozzle chamber temp, °R	4039	4860
Nozzle chamber pressure, psia	735	1000
Nozzle exit dia., ft.	—	13.6
Nozzle expansion area ratio	12	500
Specific impulse, vac, sec	—	923

## Growth Capability Composite Fuel Elements

	<u>75K NTR</u>	<u>100K NTR (Upated)</u>	<u>100K NTR (New Nozzle)</u>
Pump flowrate, lb/sec	81	108	=
Pump discharge press., Psia	1544	2059	1755
Turbine flowrate, % pump	50	67	43
Turbine inlet temp, °R	1000	1000	=
Turbine inlet press., psia	1412	1883	1539
Turbine pressure ratio	1.25	1.25	=
Reactor inlet press., psia	1130	1506	1231
Reactor power, MW	1645	2194	=
Reactor core flowrate, lb/sec	81	108	108
Nozzle Chamber temp, °R	4860	4860	4860
Nozzle chamber press., psia	1000	1333	1000
Nozzle exit diameter, Ft	13.6	13.6	15.7
Nozzle Expansion ratio	500	500	500
Specific impulse - vac, sec	923	922	923

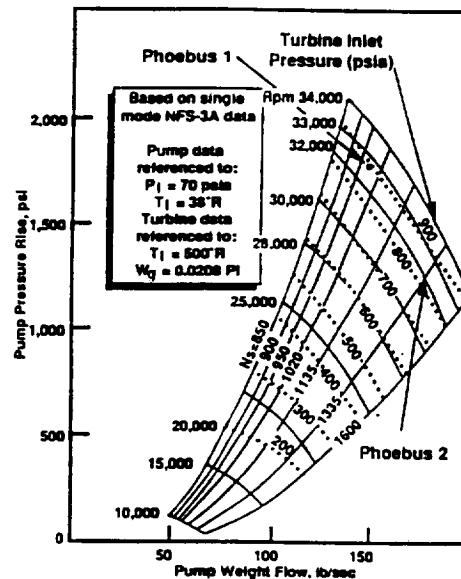
Figure 5





Rockwell International  
Propulsion Division

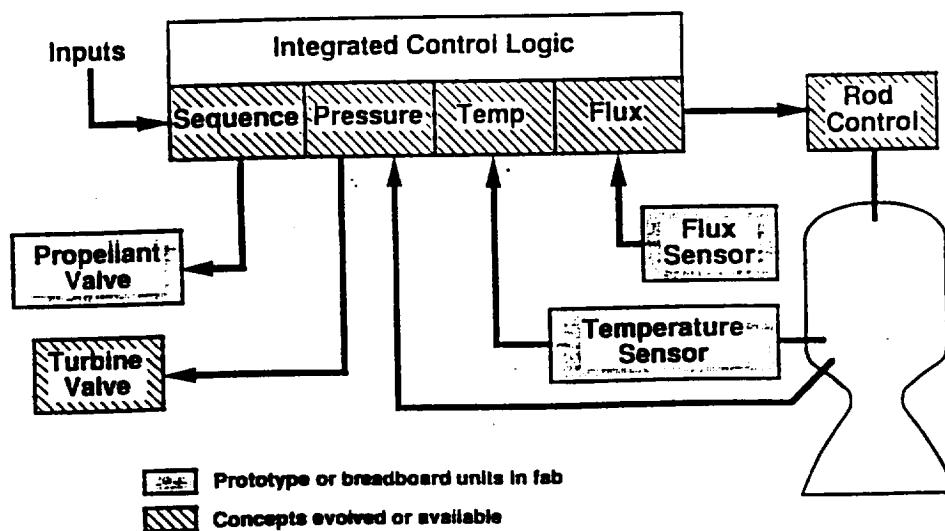
## NFS-3B Feed System Dual Mark 25 Turbopumps



90c-8-23B  
M738

Figure 7

## NTR Integrated Pneumatic-Fluidics Control System



Rockwell International  
Propulsion Division

90c-8-16A  
M738

